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Heat Tube Induction Heating Systems Stabilized Design

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Abstract

Heat tube induction heating systems are increasingly used at oil and gas production and petrochemical facilities. The existing requirements for explosion-proof electric trace heaters are not subject to induction systems; in particular, the sheath maximum temperature calculation methods are not applicable. In this paper there has been suggested a set of worse operating conditions and a calculation method to predict the heater maximum temperature that can be used when creating a stabilized design of heat tube induction heating systems.

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1. Introduction

Because of the promotion of Russia's major oil and gas producing regions to the North of West Siberia and to East Siberia, and further on to the Arctic region, and in connection with transfer to production of highly viscous products and with the increasing demands for technological processes stability, an application of electric heating systems is becoming more widespread. If in the South of Tyumen region, the main oil-and-gas production region of Russia, the share of electric heating installed capacity, according to expert estimates, is about 5% (the Uvat group of oil fields), while in the North of Krasnoyarskiy Krai, the neighboring region, it has reached 30% (Vankor oil and gas field). Of course, this contributes to the fact that the electrical resistance trace heating systems must meet the most serious technical and economic efficiency demands. On the other hand, modern economic realities require fast and high-quality construction, even in sparsely populated regions, which include the Arctic and East Siberia, as well as their further economical operation [1]. For this reason the ferromagnetic heat tube induction heating systems can be widely used as they allow creating heated technological facilities from modules in factory polyurethane thermal insulation, thus transferring part of the heating system elements installation and quality control, as well as insulation and its protection to the plants located in the economically developed areas of the country. Besides, cable (inductor) installation and, if necessary during repair work, uninstallation in heat tubes in the processing areas, are objectively easier and faster than directly on the surface of the heated facilities.

2. Application of heat tube induction heating systems in explosive zones

Application of heat tube induction heating systems is currently limited by some unsolved technical and scientific problems. Thus, the heat tube induction heating systems, usually called skin effect heating, in which the heat tube is used as a converse conductor, is widely applied for heating long straight objects, but its use for heating branched piping systems of processing areas, vessels and other objects with various complex heated surfaces is limited by the system design features requiring serial galvanic coupling of all the heat tubes in the system and their further sealing. This limitation is absent in the induction system of heat tube heating by eddy currents where the heat tube is not used as a converse conductor; but until recently there were no explosion proofing solutions suggested for this system, which is required for the system application at most oil and gas production and petrochemical facilities.

One of the most important issues of electrical trace heating explosion proofing is to ensure the maximum temperature of the heating system elements sheath at a level not exceeding the T-rating in the explosive zone [2, 3]. This is solved by using temperature sensors and special automatic equipment for heating system disabling when it is overheating, which is less preferable, or by using a heating system with a stabilized design, that is, with such parameters, when the heater temperature spontaneously stabilizes at a level below the maximum allowable one under the most adverse conditions. The existing standards for explosion-proof electrical trace heating systems rule out the extent of their requirements to induction systems [4]. The induction heating system standards do not contain any requirements for the stabilized design [5]. We have developed a stabilized design of heat tube induction heating systems; in particular, for a systems approach there has been suggested a set of unfavorable operating conditions, typical for induction systems, and a heater sheath maximum temperature calculation method has been developed and studied.

3. Heat tube induction heating system stabilized design

3.1. Worse operating conditions for induction heating system

Two elements serve as a heater in the heat tube induction heating system: the very heat tube and an inductor, located coaxially inside the heat tube. Since the heat losses from the heat tube and the inductor are directed into the environment, assuming low thermal resistance of the heat tube, which is made of steel, it can be stated that the most heated heater sheath will be the inductor sheath. Of course, the design of the explosion-proof heat tube induction heating system provides for sealing the internal space of the heat tube from the environment, but this sealing is not associated with the used types of heater explosion-proofing. Therefore the explosive mixtures can penetrate inside the heat tube and getting in touch with the inductor, for example, if seal failure due to mechanical damage.

The calculation of a stabilized design, therefore, will include three steps: finding the temperature of a heated facility under worse operating conditions, finding the temperature of a heat tube, which will determine the environment temperature for the inductor and defining the temperature of the inductor sheath.

For the heat tube induction heating system the following set of worse operating conditions has been suggested:

- The maximum ambient temperature shall be 40 °C, if the object of heating is not defined otherwise; in this case it is assumed that the electrical heating system may be incorporated into the work during the warm period of the year, for example, to check the performance, even if its operation in this period is not provided for by the project.
- Absence of wind, as it decreases heat transfer to the environment.
- Absence of the reserve coefficient, providing for an increase in heat loss into the environment due to the installation and operation conditions.
- Absence of temperature regulation, even if it is provided for by the project, with the aim to simulate a temperature sensor failure.
- The heater operates at a voltage exceeding the design working voltage by 10%, which corresponds to the maximum allowable voltage excess in accordance with the electricity quality standard.
- It is assumed that the heater operates at minimum specific resistance, resulting in higher emitted heat.

- The heat tube is completely surrounded by thermal insulation, which thickness and type correspond to the thickness and type of the insulation of the heated object, except the area of contact with the heated object if the reliability of this contact is ensured by the use of special means: welding, heat-conducting paste etc.
- The inductor axis coincides with the heat tube axis.

3.2. Assumptions and provisions adopted for the maximum sheath temperature calculation

In practice, the inductor is often freely laid in the heat tube, and therefore contacts its inner walls in a complex way: sometimes by small areas, sometimes does not contact at all. As the space between the inductor and heat tube is filled with air, the thermal conductivity of which is lower than the thermal conductivity of the inductor electrical insulation, to calculate the highest inductor temperature it is assumed that the inductor is removed from the heat tube walls to the maximum, i.e. the inductor axis coincides with the heat tube axis. Thus, the inductor is all round surrounded by an air layer of maximum thickness.

The maximum heat power output in the heat tube shall be provided by calculation at the heating system design stage. The recommended ratio of heat power released in the heat tube and that released in the inductor, is respectively 80% to 20%. However, in induction systems, the current depends on voltage nonlinearly, as with an increase in the current the magnetic permeability of the ferromagnetic heat tube also increases and so does the thickness of the skin-layer, which leads to lower resistance. Therefore, although the relation between the induction system power and the supply voltage is steadily increasing, with increasing voltage redistribution of power between the inductor and heat tube occurs, which should be considered in calculation [6]. It is also necessary to consider that electromagnetic parameters of both the inductor and heat tube depend substantially on temperature; that is why the heater maximum temperature calculation requires several iterations [6].

Assumptions made in the calculations:

- Permanence of distributed electromagnetic, thermal and structural parameters along the heater length.
- Heat tubes are placed on the surface of the heated object at a distance from each other not less than 3 diameters of the heat tube, which contributes to uniform

heat distribution on the object; the heat tubes on the heated objects made of materials with a low heat conductivity factor, for example, of polyethylene, should be placed at the maximum possible distance from each other.

- Since the heater length is much greater than its diameter, we neglect heat losses through the ends of the heater.
- Heat transfer between the inductor and the heat tube only occurs through the gap due to thermal conductivity, that is, there is no convection in the gap.
- Thermal parameters of the heater are not temperature dependent.
- The heat tube and inductor have cylindrical form.
- The heater heating power is fully transferred to the heated object; heat flows from the heater into the environment through the insulation are neglected.
- If the electrical heating system consists of several heaters, they are identical in their physical and design parameters.
- Normally induction systems do not provide for additional heaters for heating flanges, valves, etc.; thus in these places the temperature of the heater may be minimal; in electrical resistance trace heating systems, where an additional amount of heaters is provided for, there may be the highest temperature on their surface [7].

The last assumption ensures that when the heat tube induction heating system stabilized design is checked with system approach [2, 3] during an experiment such items as flanges, valves, etc. can be omitted.

4. A heater sheath maximum temperature calculation method

To calculate the maximum temperature of the heater sheath with a stabilized design the following methodology is suggested. The inductor sheath temperature is calculated by the equation (1).

$$T_{max} = \Delta T + T_O \tag{1}$$

where T_{max} is the heater sheath maximum temperature, ΔT is the temperature differential between the heated object and the heater sheath, T_O is the temperature of the heated object.

Applying the known methods of calculation of thermal losses capacity the heated object maximum temperature is determined under worse operating conditions. For example, for piping the calculation can be performed in accordance with equation (2).

$$T_O = P_h \cdot \left(\frac{\ln\left(\frac{D_{2i}}{D_{1i}}\right)}{2 \cdot \pi \cdot \lambda_i} + \frac{1}{11,6 \cdot \pi \cdot D_{1i}} \right) + T_a \tag{2}$$

where P_h is heating system specific power under worse operating conditions, λ_i is thermal insulation heat conduction coefficient under medium temperature, D_{1i} is the thermal insulation inner diameter, D_{2i} is the thermal insulation outer diameter, T_a is the ambient temperature under worse operating conditions.

Temperature differential ΔT is made up by temperature differential on design elements of the heated object and the heater in accordance with the equation (3).

$$\Delta T = \Delta T_O + \Delta T_h + \Delta T_{ir} \tag{3}$$

where ΔT_O is the temperature differential on the walls of the heated object, ΔT_h is the temperature differential on the heat tube weld, or on the layer of thermal paste, ΔT_{ir} is the temperature differential in the air gap between the heat tube and inductor. $\Delta T_h = 0$ if the heat tube is completely surrounded by the heated object, for example during concreting the heat tube in the heated floor.

$$\Delta T_O = P_t \cdot \frac{b_O}{\lambda_O \cdot t} \tag{4}$$

where P_t is heating capacity of one heater of the heating system under worse operating conditions, b_O is the thickness of the heated object wall, λ_O is thermal conductivity coefficient of the material of the heated object wall under medium temperature, t is the width of the contact zone between the heater and the heated object (for example, the width of the weld or thermal paste).

$$\Delta T_{ir} = P_t \cdot \frac{b_t}{\lambda_t \cdot t} \tag{5}$$

where b_t is the mean thickness of the heat-conducting wall between the heater and the heated object, λ_t is heat conductivity coefficient of the material of the heat-conducting wall under medium temperature.

$$\Delta T_h = P_{ir} \cdot \frac{\ln\left(\frac{D_2}{D_1}\right)}{2 \cdot \pi \cdot \lambda_c} \tag{6}$$

where P_{ir} is the inductor specific power of one heater of the heating system under worse operating conditions, λ is the heat conductivity coefficient of the air gap under medium temperature, D_{1c} is the inductor inner diameter, D_{2c} is the heat tube inner diameter.

This method provides that the heating power of a heater is distributed evenly over the heated object, and thus must be used to calculate a stabilized design of systems heating objects made of materials with high thermal conductivity, for example, steel. For other objects it is necessary to use more accurate methods of calculation such as calculation by finite element method.

5. Calculation of the heater sheath temperature by finite element method

The adequacy of the proposed methodology of calculating the sheath maximum temperature of a heater with a stabilized design is checked by calculating the heater sheath temperature by finite element method in Elcut software for steel pipeline with the diameter of 377 mm with a thickness of polyurethane insulation of 100 mm, the insulation thermal conductivity coefficient of 0.036 W/m·°C, the heat tube diameter of 32 mm, the inductor made of copper, the inductor power – heat tube power ratio in normal operation mode of 20 to 80, the number of heat tubes 2 pieces. The remaining initial data are given in table 1. Figure 1 shows the comparison of the results of calculation of heater sheath maximum temperature according to two methodologies.

Table 1: Initial data for calculation of heater temperature.

	T_a	D_{2c}	D_{1c}	b_O	λ	λ_O	b_t	t	λ_t
Value	40 °C	26 mm	6.37 mm	10 mm	0.022 W/m·°C	75 W/m·°C	8 mm	32 mm	0.70 W/m·°C

As it is evident from Figure 1, the proposed method describes with satisfactory accuracy the heater maximum temperature, the divergence of the curves, calculated according to different methods, not more than 6%, and is connected with more accurate calculation of contact area of the heat tube and piping according to the results of modeling. The calculation results by the proposed method are not conservative, which is important for stabilized designs. If it is necessary to reduce the maximum temperature of the heater sheath to match T-rating of the explosive zone the proposed technique can be used to determine the solution to this problem. Figure 2 and Figure 3 show the diagrams of relations between the heater maximum temperature and cross-sectional area of the inductor and the heater maximum temperature and the heat tube diameter, ceteris paribus.

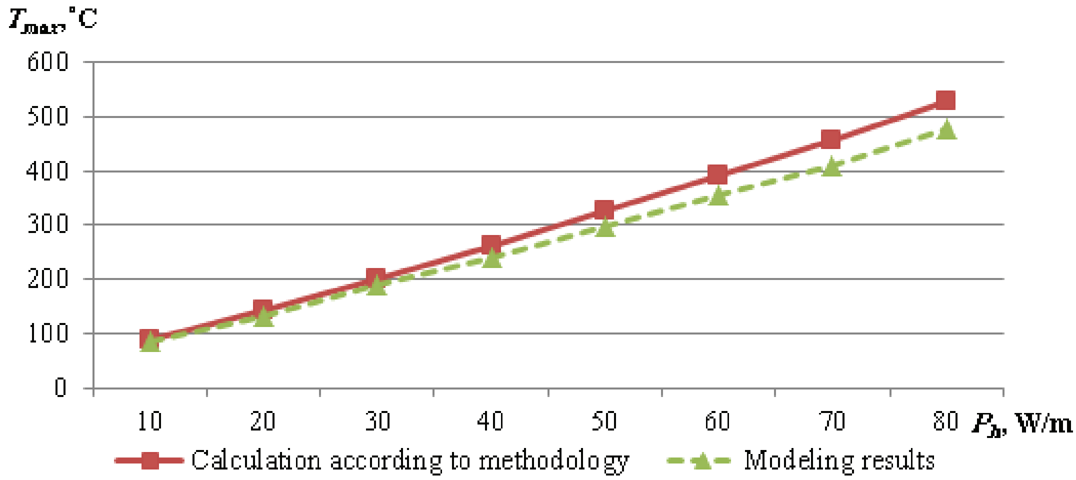

Figure 1: Comparison of the results of calculation of heater sheath maximum temperature according to the suggested method and modeling results.

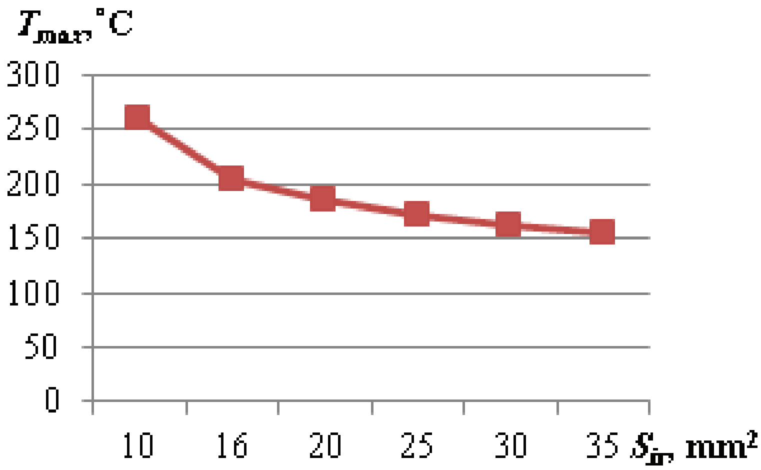

Figure 2: Diagram of relations between the heater maximum temperature and cross-sectional area of the inductor.

6. Conclusion

There has been suggested a stabilized design of heat tube induction heating systems which is a design model including worse conditions for operating these systems and a method of calculating the temperature of inductor as part of the system with the maximum sheath temperature have been defined. Mathematical modeling by the finite element method in Elcut software showed that this calculation method is reliable.

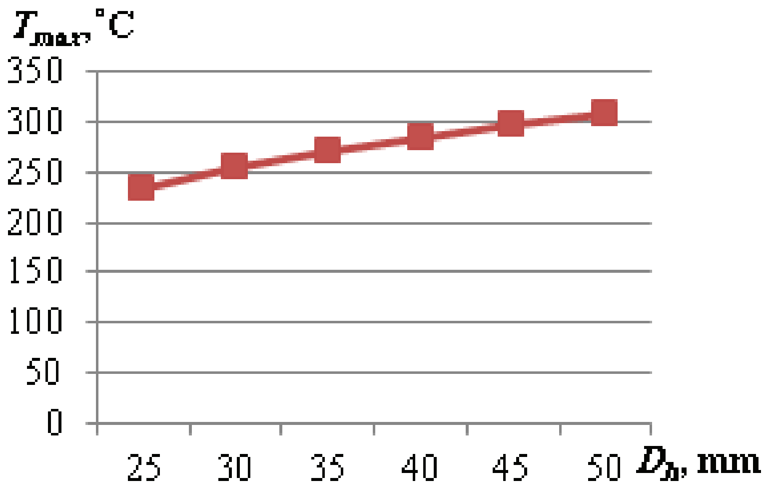

Figure 3: Diagram of relations between the heater maximum temperature and the heat tube diameter.

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